THE SWELL CLIMATE OF THE SOUTH AUSTRALIAN SEA

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Summary

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The Southern Ocean swell continually impinges on South Australian coastal waters. In this study we present simple formulae which predict the swell height at several locations in the South Australian Sea from swell height data in the open sea south of Eyre Peninsula, which are available in real time from the Bureau of Meteorology. The predictions are based on the state of the art wave model SWAN, and indicate that the major factor which determines the coastal swell climate is the direction of approach of the open ocean swell. From these predictions, bottom orbital currents can be computed, which are a fundamental factor in the marine ecology of the South Australian Sea. The formulae can also be used (at own risk) on a routine basis by mariners and surfers.

KEY WORDS: Swell, marine ecology, South Australia.

Introduction

The swell generated in the Southern Ocean south west of Australia has been recorded to be the largest of any in the world's oceans (Chelton *et al.* 1981). However, the swell in the semi-enclosed waters of South Australia is generally considered insignificant. This transition between the open ocean and coastal waters controls many aspects of the South Australian marine environment. The seasonal rhythm for the swells is a reliable signal on which the marine ecology of the surf zone depends. Southern Ocean storms also from time to time produce exceptional swell events which ventilate the interior of the coastal seas by the intensity of the bottom orbital currents that they generate. This study shows that the effects of swell can be reliably estimated, and provides a simple predictive formula which can be used by ecologists to classify marine environments and also by mariners and surfers to make real time forecasts for a specified coastal location. Specifically, we investigate the swell energy band as it propagates from the open ocean south of South Australia (Fig. 1(a)) into the South Australian Sea (Fig. 1(b)), which comprises (Bye 1976) the semi-enclosed waters of Spencer Gulf, Gulf St Vincent, Investigator Strait, Backstairs Passage and Encounter Bay, extending out over the continental shelf to the 200 m contour, bounded to the west by Cape Carnot and on the east by Cape Jaffa (Fig. 2).

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Fig. 1(a). Example of open ocean swell observed in the Southern Ocean, from RV Southern Surveyor (photograph: CSIRO Marine Laboratories, Hobart).

Fig. 1(b). Example of swell approaching the beach, West Bay, Kangaroo Island in February 1998.

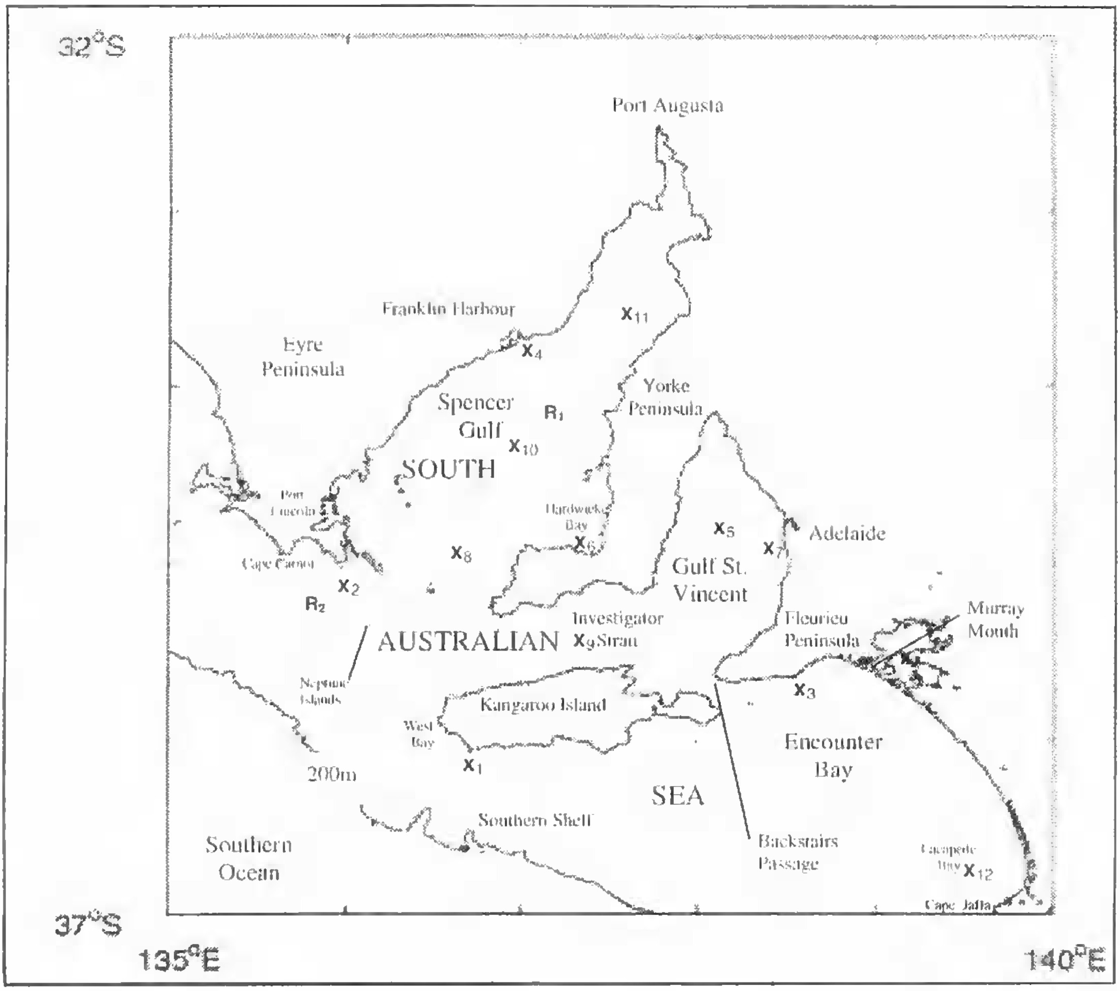

Fig. 2. The South Australian Sea with points of interest as mentioned in the text. x_i - indicate the positions of forecast formulae listed in Table 1. R_i show wave observation sites.

Wave Data

The only extended series of measurements of the Southern Ocean swell along the South Australian coastline was conducted by Steedman Science and Engineering of Perth, Western Australia, between May and October 1984 at seven measurement sites in the Great Australian Bight. These data have been analysed by Provis & Steedman (1985)[1], who noted a reduction in significant wave height by a factor of about two as the waves moved from the deepwater wave recorder in 1150 m of water, across the shelf towards the coast to the shallowest wave recorder in 26 m of water. Significant wave heights in excess of 5 m were recorded on several occasions, and waves of over 10 m were recorded during a July storm as far inshore as the 75 m depth contour. The significant wave period remained almost constant at about 15 s at all seven measurement sites. This period is very similar to the dominant swell period (16 s) in the classical experiment of Munk *et al.* (1963) in which swell was observed to travel across the Pacific Ocean to Alaska from Southern Ocean winter storms, almost without loss of energy.

An interesting feature of the measured open ocean wave spectra is that they are unimodal, i.e. there are no distinct wind sea and swell peaks. Only at times of very low incident swell were separate peaks observed. Young & Gorman (1995) suggest that the

[1] Provis, D. G. & Steedman, R. K. (1985) Wave measurements in the Great Australian Bight. Paper presented at Australasian Conference on Coastal and Ocean Engineering. IEAust., Christchurch, NZ 1985. (unpub.).

proximity of the site to the Southern Ocean storm belt does not provide sufficient time for the wavefield to disperse and a bimodal (wind wave and swell) wave spectrum to develop.

No open sea wave measurements appear to be available for the summer season, but in April 1998, a new series of wind wave and swell measurements was initiated in the South Australian Sea and the adjacent Southern Ocean using electric field measurements (Heinson *et al.* 1998; Hemer 1998[2]; Hemer *et al.* 1999). The details of this program are reported elsewhere, but for our purposes an important feature was the near simultaneous observation of wave spectra on the Southern Shelf and in Spencer Gulf with which the predictions of the wave model can be compared. Apart from these measurements,

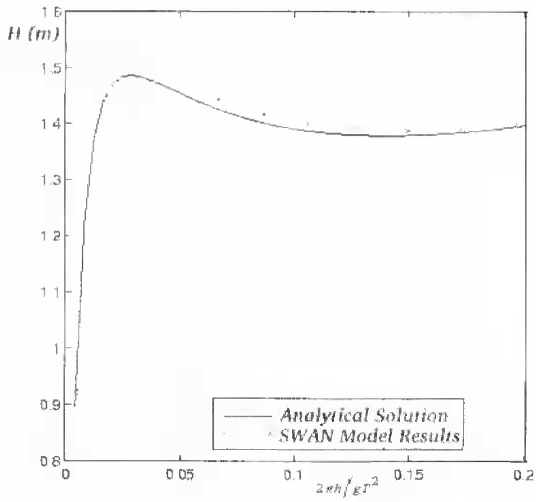

Fig. 3. Comparison of SWAN wave heights with the analytic solution of Nielsen (1983) for an incoming swell of period (T = 12 s) and height (H_o = 1.4 m) running up a plane of slope 1.125 x 10^{-3} with a quadratic bottom friction coefficient, C_f = 0.015. The abscissa is the ratio of the water depth (h) to incoming wavelength ($gT^2/2\pi$) where g is the acceleration of gravity and the ordinate is the wave height (H). The SWAN results (x) are computed on a 4 km grid.

[2] Hemer, M. (1998) A Wave Study of the South Australian Sea: Prediction, Observation using Electric Field Measurements, and Application to Sediment Resuspension Processes. BSc (Hons) Thesis, The Flinders University of South Australia (unpub.).

[3] Bye, J. A. T., Gunn, B. W. & Nikpalj, C. V. (1975) The Wave Climate off Cape Jervis, South Australia between June and November, 1974. Flinders Institute for Atmospheric and Marine Science Research Report, No. 17. (unpub.).

[4] Culver, R. & Walker, D. (1981) Redcliff Wave Atlas. The University of Adelaide Department of Civil Engineering report. (unpub.).

[5] Walker, D. (1989) An Efficient Wave Hindcasting Model. 9th Aust. Conf. Coast. & Oc. Engng. Adel., 4-8 Dec. 1989. 117-121. (unpub.).

[6] SWAN (1998) SWAN web page. http://swan.ct.tudelft.nl

wave studies in the South Australian Sea (Bye *et al.* 1975[3]; Culver & Walker 1981[4]; Walker 1989[5]) have usually neglected the swell signal.

The SWAN Wave Model

The SWAN wave model (Simulating **WA**ves **N**earshore) is a directional spectral wave model written by the Coastal Engineering group of the Delft University of Technology, Netherlands (Ris *et al.* 1997) especially for coastal seas. In the formulation of the model, many wave propagation processes are implemented. These include wave propagation, wave refraction due to bottom shoaling and refraction and reflection by currents. Along with these effects, the model also includes generation of wave energy by wind, dissipation of wave energy by whitecapping and depth induced wave breaking, frictional dissipation due to bottom drag and redistribution of energy over the wave spectrum by non-linear wave-wave interactions (SWAN 1998[6]). Limitations of SWAN are that it does not account for diffraction or reflections, and hence it is unsuitable for regions where wave height variations are large within a horizontal scale of a few wavelengths (Ris *et al.* 1997) and regions of 'steep beaches' (i.e. cliffs, harbours etc.) SWAN is therefore a 'state of the art' model for the present study of the propagation of swell into the South Australian Sea. It is important however to carry out two basic checks on the model.

Firstly, the analytic model of Nielsen (1983) was compared with the results of the SWAN model over a plane sloping bed under variable conditions in which a plane wave was propagated into the domain at the deepest end (Hemer 1998[2]). Figure 3 shows that, for a typical swell period of 12 s, and a quadratic bottom friction coefficient (C_f) of 0.015,

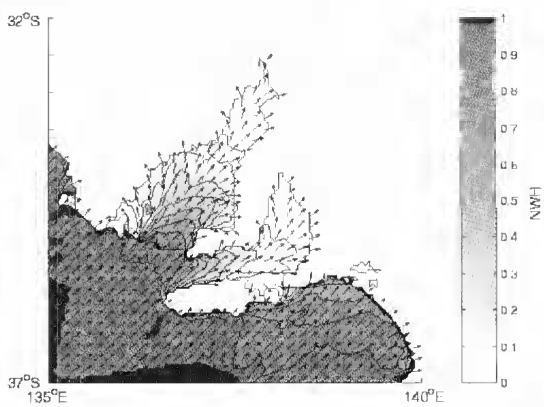

Fig. 4. The swell wavefield in the South Australian Sea predicted by the SWAN model for C_f = 0.015 and D_o = 230°. The contours show normalised wave height (NWH); contour interval 0.1, and the arrows indicate the direction of swell propagation.

such as would occur over sandy beaches (Jonsson 1966), the analytical solution and the numerical solution are in very good agreement for the grid interval 4 km. The SWAN model simulations presented below are run on a uniform 100 x 100 rectangular grid of grid interval, 4.5 km on which the bathymetry was taken from the Australian Geological Surveying Organisation (AGSO) 30 arc second digital file. Secondly, we compare the predictions of SWAN for swell propagation into Spencer Gulf, with the April 1998 wave observations and the predictions of the Bureau of Meteorology Southern Ocean wave model (WAM) which is run in operational mode with wave fields issued at 0000, 0600, 1200 and 1800 UTC, and is available from the Bureau of Meteorology (Bureau of Meteorology, 1999[7]). It is convenient to present the results of the comparison at the end of the next section after the SWAN model outputs have been described.

Results

Figure 4 shows the normalised wave height[8]

$$NWH = {}^{H}\!/_{H_o} \qquad (1)$$

where H is the swell wave height, and H_o is the open ocean input swell height, and also the wave direction (D) for swell of period 15 s and H_o = 3.5 m propagating from the direction, D_o = 230°. It is observed that the swell begins to lose its energy as soon as it enters the region. More energy is lost when the wave front reaches Kangaroo Island (KI) with the coast absorbing the energy of some directional components of the wave. Large wave heights occur at the coast of KI, (NWH ~ 0.9) close to the coast. These results agree with anecdotal observations of large wave heights on the southern and western coasts of KI.

Kangaroo Island provides a significant blockage to wave energy influx into Gulf St Vincent (GStV), and the wave energy that enters GStV is due to refraction as the water depth decreases and the waves "wrap" into Investigator Strait, becoming more perpendicular to the depth contours. Significant loss of wave energy is observed with waves propagating eastward through Backstairs Passage, so that almost all the wave energy due to swell in GStV originates from waves propagating through Investigator Strait.

[7] Bureau of Meteorology (1999) Bureau of Meteorology http://www.bom.gov.au

[8] Wave Height is the significant wave height defined by the relation $H = 4\sqrt{E}$ in which E is the wave energy (Phillips 1977).

[9] Provis, D. G. & Steedman, R. K. (1985) Wave Measurements in the Great Australian Bight. Paper Presented at Australasian Conference on Coastal and Ocean Engineering, 7th Ann. Christchurch, New Zealand, 1985 (unpub.)

Waves at the head of GStV, the western end of Backstairs Passage and the metropolitan coast of Adelaide all show wave heights less than 10% of the input height (NWH < 0.1). In Investigator Strait, refraction is seen to have an effect with the waves becoming more and more perpendicular to the coast and the northern coast of KI shows regions where waves have refracted more than 180° from the input wave direction. Within the gulf, a northward dominance of wave propagation still exists, but a significant spreading towards the coast at all locations is observed. Wave height is observed to increase markedly along the southern side of Fleurieu Peninsula, with almost no waves at the western end (NWH < 0.1) to significant wave energy at the Murray Mouth (NWH ~ 0.6). Propagation into Encounter Bay shows very little refraction, due to the waves initially travelling almost normal to the depth contours.

The propagation of swell into Spencer Gulf (SG) shows a continual loss of wave energy (or wave height) with decreasing water depth towards the head of the gulf. Large loss of wave energy is observed in the various "shadow zones" of SG such as Hardwicke Bay. Again clear evidence of refraction is observed with wave direction becoming nearly perpendicular to the coast in all regions. Within Hardwicke Bay, waves are observed to be propagating in directions rotated more than 90° from the input swell direction. In the vicinity of Port Lincoln, waves are observed to have refracted by 180°, with waves travelling in the opposite direction to the input swell. The general pattern of wave energy in SG shows a spreading and loss of wave energy towards the sides of the gulf. The south-western coast of Eyre Peninsula shows very little loss of energy before reaching the coast. On the west coast of Eyre Peninsula, however, the observations of Provis & Steedman (1985)[9] show a halving of wave height from deep water to the coast. Boundary effects preclude a comparison between simulation and observations in this region but a similar reduction factor occurs in the model in Encounter Bay. Islands in the opening to SG such as the Neptune Islands are seen to block some wave energy from propagating into the gulf.

The wave period of the swell remains at a constant 15 s throughout the model domain. This result is expected given that no further wind forcing within the region is present. A reduction of wavelength of ~30% occurs within the gulf, due to the decrease in wave speed with decreasing water depth (see eqn (5)). From the model results, the maximum bottom orbital velocity, U_*, can also be derived (Hemer 1998[2]), (see eqn (4)). It is found that a balance exists between the decreasing wave heights and wavelength and the decreasing water depth. The

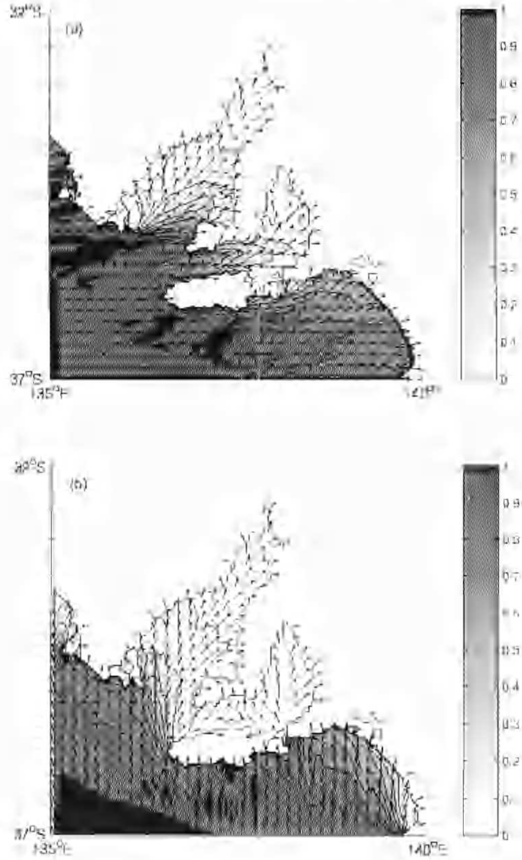

Fig. 5. As for Figure 4. (a). A westerly swell $D_o = 260°$. (b). A south-easterly swell. $D_o = 160°$.

largest U values (for H_o = 3.5 m) of ~0.5 ms^{-1} (1 knot) were observed in the shallow water of the south coast of Kangaroo Island. Within the gulfs, water depths were much less, but wave energy had dissipated such that U values, 0.15 ms^{-1} (0.3 knot), were less than half of the magnitude on the south coast of Kangaroo Island.

A number of sensitivity studies (Hemer 1998[2]) have been carried out by varying input model wave heights, directions, periods, bottom friction and wave breaking parameters, and model runs were also carried out with a uniform depth South Australian Sea. Variation of input swell wave heights (H_o) was found to cause minimal changes in the NWH throughout the South Australian Sea with slightly lower NWH (greater dissipation) for a larger input wave height. Changing the input wave period also only had small effects on the wave heights and directions within the South Australian Sea for typical swell periods.

The swell propagation is also insensitive to the variation of bottom friction, such as might be caused over seagrass beds. In the coastal zone however, bottom friction is found to cause significant decreases in predicted wave heights, e.g. wave heights in the surf zone are approximately 25% greater if frictionless conditions are assumed for coastal zone depths less than 10 m. Finally, specifying the South Australian Sea to have a uniform depth of 50 m gave almost the same reduction in wave height with progression into Spencer Gulf and Gulf St Vincent, as for the depth varying topography. These results suggest that the dominant source of energy loss in the South Australian Sea is absorption of wave energy at the coast by frictional loss in the shallows and wave breaking on coastal beaches in depths less than 10 m, rather than any form of depth induced effect in the interior of the sea.

We conclude from these sensitivity studies that the major source of swell height variability in the South Australian Sea is the direction of approach of the deep sea swell. Figure 5 illustrates the effect of a rotation of the direction of approach of the deep sea swell, either towards a westerly or a south-easterly direction. A westerly swell penetrates into Investigator Strait, and is refracted into Spencer Gulf along the western coast of Yorke Peninsula (Fig. 5(a)). On the other hand, Investigator Strait is well protected from the south easterly swells, more typical of Summer weather conditions, which are refracted into Spencer Gulf on the eastern coast of Eyre Peninsula (Fig 5(b)). This pattern occurred on April 20 1998 when wave observations were made in mid Spencer Gulf (R_1 in Fig. 2). The observed swell height and direction were respectively, H = 0.13 m, and $D = 230°$, whereas south of Eyre Peninsula the WAM model predicted the swell height and direction, H_o = 1.8 m and $D_o = 160°$, from which NWH = 0.08. The SWAN model prediction shown in Fig. 5(b) yields NWH = 0.08, and direction $D = 223°$, in good agreement with the observations. The accuracy of the WAM model was also assessed by comparison with observed wave data obtained south of Eyre Peninsula on April 16 1998 (R_3 in Fig. 2). The predicted swell parameters, H_o = 1.5 m and $D_o = 220°$ were in good agreement with the observations of H_o = 1.3 m and $D_o = 225°$ (Hemer 1998[2]).

We conclude that the predictions of the WAM and SWAN models can be successfully linked to provide reliable swell prediction formulae for the South Australian Sea, which are presented in the next section.

Swell Prediction Formulae

The isolation of wave direction as the dominant influence on normalised wave heights (NWH) within

TABLE 1. *The coefficients of the swell forecasting formula (eqn (2)) and swell heights (H) and maximum bottom orbital velocities (U) for swell propagating from the directions 230°, 260° and 160° for various locations in the South Australian Sea.*

Position	h(m)	a_4 (x10^{-9})	a_3 (x10^{-6})	a_2 (x10^{-3})	a_1 (x10^{-1})	a_0
1. Cape du Couedic	47	-6.8842	6.3809	-2.2079	3.3862	-18.512
2. Cape Catastrophe	50	-68.622	58.499	-18.517	25.781	-132.24
3. Fleurieu Peninsula	27	34.150	-27.419	8.0454	-10.190	47.388
4. Franklin Harbour	11	12.867	-10.714	3.2704	-4.3259	20.988
5. Mid Gulf St Vincent	33	-2.2965	1.8031	-0.51453	0.63910	-2.9210
6. Hardwicke Bay	10	2.0027	-1.7867	0.58009	-0.80486	4.0597
7. Adelaide	10	5.8435	-4.8575	1.4918	-1.9994	9.9339
8. Lower Spencer Gulf	46	32.394	-26.892	8.1539	10.644	50.701
9. Investigator Strait	36	-7.7955	5.9928	-1.6607	1.9985	-8.8503
10. Mid Spencer Gulf	28	28.793	-23.973	7.3154	-9.6709	46.871
11. Upper Spencer Gulf	12	4.2561	-3.5376	1.0781	-1.4241	6.9002
12. Lacapede Bay	39	8.2295	-6.6782	1.9008	-2.1954	9.0546

	H^s_{230}	H^s_{260}	H^s_{160}	U^s_{230}	U^s_{260}	U^s_{160}
Position		(m)			(ms^{-1})	
1. Cape du Couedic	4.73	4.84	3.85	0.77	0.78	0.62
2. Cape Catastrophe	4.47	4.52	4.29	0.65	0.66	0.63
3. Fleurieu Peninsula	2.91	2.31	1.93	1.10	0.87	0.73
4. Franklin Harbour	0.73	0.42	0.22	0.98	0.56	0.29
5. Mid Gulf St Vincent	0.36	0.55	0.07	0.10	0.16	0.02
6. Hardwicke Bay	0.50	0.48	0.13	0.77	0.74	0.20
7. Adelaide	0.59	0.63	0.34	0.91	0.97	0.52
8. Lower Spencer Gulf	3.44	2.69	1.09	0.58	0.45	0.18
9. Investigator Strait	1.81	2.76	0.24	0.45	0.68	0.06
10. Mid Spencer Gulf	1.63	0.92	0.45	0.58	0.33	0.16
11. Upper Spencer Gulf	0.24	0.14	0.07	0.28	0.17	0.09
12. Lacapede Bay	4.46	3.51	3.15	0.86	0.67	0.61

the South Australian Sea suggested that swell prediction formulae could be obtained. The set (150°, 160°, 175°, 190°, 200°, 215°, 222°, 230°, 237°, 245°, 253° and 260°) was chosen from SWAN runs as representative of the swell energy window from which waves propagate, and the NWH was determined at selected grid points. Using the twelve runs, a polynomial of order 4 was fitted at each grid point to interpolate NWH over the range of propagation directions, D_0 = 150° - 260°.

$$NWH = a_4 D_o^4 + a_3 D_o^3 + a_2 D_o^2 + a_1 D_o + a_o \quad (2)$$

The coefficients are shown in Table 1 for the positions in the South Australian Sea illustrated in Fig. 2. It is emphasised that, for the coastal sites, eqn (2) predicts the incoming swell heights outside the surf zone at a depth of 10 m. Table 1 allows a simple calculation of swell heights to be made using the deep sea swell height and direction from the WAM model output, over the range of directions for which significant swell energy propagates into the South Australian Sea.

The travel time, τ in h, for swell over a distance, *d* in km, assuming deep water wave conditions, is

$$\tau = 0.18 \, d/T \quad (3)$$

in which *T* is the swell period. For a representative travel distance of 350 km, and a swell period of 13 s, τ ~ 5 h, and hence real time forecasts for swell conditions can be obtained from the six hourly wavefields available from the Bureau of

[a] The authors accept no liability on the use of information given in this paper.

[b] HARRISON, P. (1997) Protecting Gulf St. Vincent: A Statement on its Health and Future. Department of Environment and Natural Resources, Adelaide, 1997. (unpub.).

Meteorology (Bureau of Meteorology, 1999[7]). It is suggested that input parameters be taken from the WAM output at the 37°S and 135°E grid point[10].

The corresponding maximum bottom orbital velocities, U, due to the swell can be calculated from eqn (2) using the formula

$$U = \frac{\pi H}{T \sinh(kh)} \qquad (4)$$

in which h is the water depth and k is the wavenumber of the swell, which can be determined from the approximate formula (Fenton 1990)

$$k \approx \frac{4\pi^2}{gT^2}\left(\coth\left(\frac{2\pi}{T}\sqrt{\frac{h}{g}}\right)^{3/2}\right)^{2/3} \qquad (5)$$

in which g is the acceleration due to gravity. The swell heights (H'_{D_o}) and maximum bottom orbital velocities (U'_{D_o}) for an open ocean swell of 5 m propagating from the directions (D_o) discussed in the previous section are representative of the most severe swell conditions likely to be encountered in the South Australian Sea (Table 1).

Conclusion

This study uses state of the art wave modelling to show the propagation of swell into the South Australian Sea. An obvious application is real time swell forecasting for mariners and surfers. The SWAN model can be also run to forecast the wind wave spectrum generated by local winds but this is beyond the present scope.

The intrinsic interest of swell is its role in sediment transport processes at the sea bottom. The example of Table 1 illustrates that a severe swell event generates very significant bottom orbital motion which resuspends sediment particles into the water column which may then be transported by tidal and wind driven currents. In order to describe the sediment transport process in coastal areas, it is essential to determine the swell climate accurately. The results of this wave study, along with developed sediment resuspension tools, will help significantly to advance the understanding of sediment and particulate transport processes in regions of concern within the South Australian Sea, for example, the Adelaide metropolitan coastline (Wynne 1984) and the mouth of the River Murray (Harvey 1996), and provide a framework for its future management (Harbison 1997[11]).

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